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ANALYSIS OF CORRECTIVE ACTIONS FOR HIGHWAY LANDSLIDES

By R. F. Baker, A.M. ASCE

HIGHWAY DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

ANALYSIS OF CORRECTIVE ACTIONS FOR HIGHWAY LANDSLIDES

By R. F. Baker,[1] A. M. ASCE

Synopsis

A semirational approach to the correction of highway landslide problems is presented in this paper. Only those failures involving earth movements are considered, and their analysis varies from methods described by some authorities in that (1) the landslide classification system is based on the mechanics of the movements; (2) a more general use of basic mechanics is made in estimating the effectiveness of a corrective measure; (3) a suggestion is made that there is more than one method for controlling a given earth movement; (4) the problem is primarily described as economic rather than academic; and (5) the statement is made that the determination of the mechanics of a landslide is more important than "the" cause. It is concluded that there is a need for a rational approach to the analysis of highway landslides and that that approach should have a scientific basis. It is also concluded that most corrective measures can be checked for stability by the use of a formula of the form used to determine the safety factor in soil mechanics. The proposed analysis is considered semirational, and for its general application, extensive development and observations are still necessary.

Introduction

Landslides are a critical problem throughout the world, but were never quite so prevalent as during the winter of 1950–1951 when there were almost daily reports of large-scale earth movements. West Virginia was greatly affected, and during the year 1950, approximately $125,000 was spent in extraordinary maintenance to resurface or remove debris from primary roads damaged by landslides. This sum does not include expenditures on secondary

Note.—Written comments are invited for publication; the last discussion should be submitted by November 1, 1953.

[1] Engr. of Soil Mechanics, State Rd. Comm., Charleston, W. Va.

roads, on permanent corrections, nor on new construction projects. Although the winter and spring of 1950 and 1951 were particularly critical with regard to landslides, the State Road Commission of West Virginia has been bothered with similar problems for many years.

Numerous publications have carried detailed accounts of landslides. One of the most comprehensive reports was prepared by George E. Ladd for the American Railway Engineering Association.[2] Another publication in which the theories of earth and rock movement are thoroughly discussed is that by C. F. S. Sharpe.[3] Karl Terzaghi, Hon. M. ASCE, not only summarized the theories of soil mechanics but showed their application to earth movements in one of his works.[4] Paul H. Price, geologist for the State of West Virginia, prepared an unpublished report in 1940 about some of the landslides that had damaged West Virginia highways, and drew conclusions as to proper procedures in design, construction, and maintenance. Extensive bibliographies are included in the publications by Messrs. Sharpe and Ladd.

However, there is no known reference that presents a systematic approach to the use of the various methods of corrective action and the types of investigation necessary. Mr. Ladd refers briefly to nearly all the methods mentioned in this paper, but suggests that the basis for design is experience—which is not too helpful either to newcomers or to those who deal with slides sporadically.[2] Those who have become familiar with one method will use (or perhaps overuse) that same method because of their familiarity with the design and construction. Also, if more than one engineer or geologist is asked to make recommendations to counteract a slide, more than one answer is almost certain. Since there is a diversity of opinion as to proper corrective action, there is an obvious need for a method of analysis and evaluation that will clarify the factors involved.

The purpose of the following analysis is to suggest an approach to the design and use of corrective measures for earth movements that are threatening or affecting highway structures. The approach is basically one of highway engineering, although use is made of soil mechanics and geology. The study is not all-inclusive since there is no attempt to study failures that involve bedrock movement, subsidences, settlements of embankments over marsh or swamp areas, rock falls, rock weathering, or failures due to earthquakes. These are fundamentally different problems involved in mass movements and, therefore, are not included. The analysis presented is suggested for use in all other cases of earth masses in motion. The writer's experience has been in an area where earth movements represent at least 90% of the highway mass movements.

Undoubtedly, the technique suggested is an oversimplification, and, for general use, would require elaboration and attention to variables. However, for numerous small earth movements where an overdesign is not too costly, where the value of the structure to be protected is not great, and where there are no trained, experienced personnel to study the slide in detail, the suggested

[2] "Landslide, Subsidences and Rock-Falls," by George Edgar Ladd, *Bulletin*, Am. Ry. Eng. Assn., Vol. 37, No. 377, July, 1935.

[3] "Landslides and Related Phenomena," by C. F. S. Sharpe, Columbia University Press, New York, N. Y., 1938.

[4] "Mechanism of Landslides," by Karl Terzaghi, *Berkey Volume*, The Geological Soc. of America, 1950.

approach will permit better engineering than is possible with only experience as a guide. When it is realized that landslides in West Virginia number in the hundreds each year, the need for an immediate, usable, and rational method of approach is understandable.

Definitions

Landslides have been defined by Mr. Ladd[2] as

> "***superficial earth movements having essentially a horizontal component, usually involving slopes varying from very gentle to very steep, but rarely involving vertical cliffs at one extreme, and level but unsupported ground at the other."

Mr. Terzaghi[4] states of landslides,

> "The term landslide refers to a rapid displacement of a mass of rock, residual soil or sediments adjoining a slope, in which the center of gravity of the moving mass advances in a downward and outward direction."

These definitions and others are in general agreement. The main difference lies in the element of time. Mr. Terzaghi states that a landslide is a "rapid displacement" as differentiated from his definition of creep which he states is a "***similar movement proceeding at an imperceptible rate***." Messrs. Ladd,[2] Sharpe,[3] and others recognize the factor of time in landslides and in the phenomenon commonly termed creep. However, there is less accord as to the mechanics involved, particularly for creep. Mr. Terzaghi divides creep into continuous and seasonal types and defines the latter as a relatively shallow failure related to changes in moisture and temperature. He defines continuous creep as a relatively deep movement produced by the force of gravity, often caused by the presence of various strata with different elastic properties, and he asserts that, when the mass is stressed below the "average shearing strength" of the system, the weaker materials deform like a "very viscous liquid." Mr. Terzaghi also writes of the "fundamental strength" of elastic materials in contrast with the "compressive strength." The former term relates to the much smaller but continuous load under which the failure of the material begins. Perhaps the most important physical distinction that Mr. Terzaghi makes between landslides and creep is that landslides involve a body of material with "well-defined boundaries," but creep may involve areas in which "***no sharp boundaries exist between stationary and moving materials." This latter statement is important because of the potential clarity in identifying the type of displacement that has occurred.

Many methods have been proposed for classifying mass movements. Messrs. Ladd[2] and Sharpe[3] give excellent resumés of past efforts as well as proposed systems. Mr. Ladd presents a method of classification that excludes the term, creep, because of the inference that time is an element, whereas time is not a factor in his other classifications. Mr. Sharpe has recommended a classification that is quite complete and includes time as a most essential factor. A brief method of classifying mass movements was advanced by Mr. Price to cover the types of landslides encountered in West Virginia.

From the viewpoint of highway engineering, there is little value in classifying earth movements in too great detail. Mr. Sharpe states that mass

movement may be classified as slides and flows. In the former, he includes all movements in which a slip-surface is involved, whereas the latter movement is a shifting of the mass and does not involve a surface of slippage. This distinction is shown in Fig. 1. From a corrective viewpoint, the difference need not be greatly amplified in order to serve adequately for classification purposes.

In this paper, four classifications of earth movements will be used, and the advantages of these classifications will become evident as the analysis progresses. Basically, the classification is a variation of a part of Mr. Sharpe's system.

Slides.—Earth movements that produce a slip-surface that is curved or partly curved in a direction parallel to movement are classified as slides. The slide area is surrounded by well-defined cracks except at the toe where "heaving" or "rolling" delineate the limits. Should the cracks be discontinuous, an earth movement could not be classified as either a slide or debris slide. Slides also produce "benches," or approximately horizontal surfaces near the top of the slide. These benches are typical of slides that have produced curved slip-surfaces. It is not unusual to find trees, poles, and houses

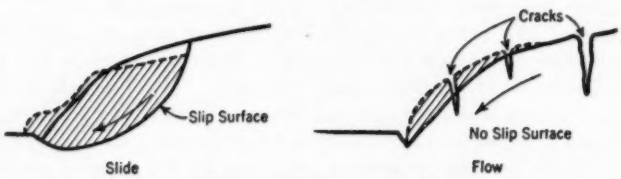

FIG. 1.—SLIDE AND FLOW IN EARTH MASSES

in a relatively undisturbed vertical condition because the failure may be deep. The earth movement is sudden, in comparison to creep and flow, and is very likely to come to a temporary rest.

Debris Slides.—This movement differs from slides in that the plane of failure is straight in a direction parallel to the direction of movement. Upon a surface investigation, a debris slide will resemble some types of slides. However, the open crack at the top of the slide will not expose a slide plane because the material breaks away, rather than sliding. Furthermore, the characteristic "heaving" or rotation at the toe of a slide will not be present for a debris slide.

Creep.—An earth movement which produces no slip-surface is termed creep. There is no clear line of cracks parallel to the movement to delineate the lateral extent of the slide area. The surface of the area contains some cracks perpendicular to the movement, but normally has a series of rolls or humps on the surface of the slide and no open cracks. Mr. Terzaghi suggests that is would be well to differentiate between seasonal and continuous creep. The distinction is based on the depth that is affected by variation in temperature and rainfall. Seasonal creep, as suggested by Mr. Terzaghi, could actually be classified as flow.

Movement is assumed to be caused by the successive failure of weaker strata or the forces being greater than the fundamental strength. With the

exception of the cause, the movements are similar to those termed talus-creep and soil-creep by Mr. Sharpe.

Flows.—This movement is essentially the same as creep except that the primary cause of displacement is defined as the presence of an excessive quantity of water. This approximates the movement termed earth-flow by Mr. Sharpe, although the definition used in this paper states that upon the development of a sliding surface a flow becomes a slide. Flows are not too common in the Appalachian province particularly within the Allegheny Plateau Province of West Virginia, and occur in soil and soil-boulder materials having a high moisture content. The slope of the transported material is correspondingly flat in comparison to surrounding topography. The movement is more rapid than creep and may be differentiated from a slide primarily on the basis of the higher moisture content, flatter slopes, lack of continuity in the cracks, lack of a slip-surface, and open cracks that do not expose a slick, sliding surface.

Rock Slides.—A movement involving bedrock material is classified as a rock slide. Rock movements should be identified as such, although this analysis does not consider corrective action. Generally, displacements involving bedrock are obvious from a surface examination, but this type is most difficult to identify if it consists of a general subsidence due to the ejection of a weak layer, or due to cavities formed by nature or by man. Open cracks develop at the top of the slide, and subsurface exploration shows the presence of rock strata.

Omitted from consideration in this study are the following types as classified by Mr. Sharpe: Rock-creep, rock-glacier creep, solifluction, mudflow, debris-avalanche, debris-fall, rock-slide, rock-fall, and subsidences. Also eliminated is failure directly attributed to earthquakes.

The terms slip-plane, surface of failure, slip-surface, and other similar terms refer to the surface that divides the mass in motion from the stable material. A curved or straight slip-plane always refers to the shape of an assumed line, which lies on the surface of failure, parallel to the direction of movement, and is considered as being characteristic of the predominant shape of the slip-surface.

Mass movement is a term used by geologists and refers to all types of rock and soil displacements in which the material moves as a mass under the force of gravity. Earth movements and landslides refer to only those mass movements occurring in soil or soil-boulder materials, specifically excluding phenomena involving the movement of bedrock.

Fundamental Considerations

Water is present as a contributing factor in almost all earth movements. The damaging action of the water is most often attributed to the weight added to the soil mass, the reduction of shear characteristics of the soil, and the lubricating action on the sliding plane. Hyde Forbes, M. ASCE, writes that, under certain conditions, seepage water could produce geochemical and physical changes in the soil and underlying bedrock.[5] Mr. Terzaghi[4] and others

[5] "Landslide Investigation and Correction," by Hyde Forbes, *Transactions*, ASCE, Vol. 112, 1947, p. 377.

assert that water produces piezometric or hydrostatic pressures that, in effect, "float" the material away. All authorities agree that the removal of water represents a sound approach to a slide correction. The importance that is placed on drainage varies. In Mr. Forbes' paper, other corrective actions are mentioned, but details are given for drainage solutions only. Mr. Ladd states that drainage represents a very favorable type of correcting action, but gives considerable coverage to other corrective measures.[6] Mr. Price states that drainage as a corrective action has been overemphasized. He points out that to drain an area successfully, the soil must be permeable and nearly free of clay. This latter statement is undoubtedly true unless excess hydrostatic pressure is relieved prior to contact with the displaced mass.

A fundamental consideration in the use of corrective measures is the fact that all mass movements will continue until the topographic bottom of the area is reached. The time required for the mass to reach the bottom may be many hundreds of years. The importance of the role of landslides as "topographic-shapers" is emphasized by Mr. Ladd,[2] who states that "***'erosion' alone, should be given less credit for playing the major role." It may be assumed that most natural earth slopes, and particularly old slides, are near an equilibrium or balance point. The works of man accelerate or decelerate the ultimate rate of movement.

For landslides whose slip-surface is at the contact point between soil and underlying rock, the failure occurs in the soil. This is pointed out by Mr. Forbes,[5] and frequently observed in West Virginia. "Failure in the soil" means that soil fails in shear, and the shear characteristics of the soil at the slip-plane can be applied in a stability analysis. If the soil merely slips over the surface of the underlying rock, the mechanics for estimating the shearing resistance before failure require an entirely different approach based on the friction value between the earth mass and the rock.

There are several methods of correcting any given highway landslide problem, but it should be realized that the correction of all earth movements is not economically feasible. The corrective measure to be used depends primarily on economics, which means that the highway engineer has a totally different approach than others engaged in solving landslide problems. Many past studies have dealt with landslides of large areas or movements that were threatening particularly valuable structures. The writer believes that some of the methods that were suggested for these types of problems are not feasible for many highway situations. Mr. Forbes mentions spending seven months to study a landslide threatening a million-dollar structure. The methods applied to that situation should not be compared with the method used to save a thousand-dollar section of highway, even if the slide were of the same magnitude. It is entirely possible that an expedient method—one that is satisfactory for a period of from five to ten years—is the best answer to a highway landslide. This approach should not be used as an excuse for poor engineering, or for the elimination of an investigation.

[6] "Landslides and Their Relation to Highways," by George E. Ladd, *Public Roads*, Pt. 1, Vol. 8, 1927, p. 21, and Pt. 2, Vol. 9, 1928, p. 153.

From a highway engineering viewpoint it is generally accepted that the solution to a landslide problem need not be a corrective action for the earth movement. The problem is not to eliminate the displacement but to correct a situation involving either costly maintenance or a threat to life, or to a structure, by the use of engineering principles.

The accurate determination of "the" cause of a landslide is not always essential to the solution of a highway landslide problem; equally important are the mechanics of the movement. For some earth movements and types of corrective measures, complete information as to the cause and the contributing factors is not needed except for academic reasons. The determination of "the" cause is often misleading since almost all landslides result from a combination of causes, with one factor being finally dominant. Of great importance is the fact that by eliminating or by modifying the effect of any one of the causes the stability will increase. The approach to landslide problems is still so uncertain that quite often engineers and geologists cannot agree on the final, decisive cause. Disagreement has arisen on the basic causes for many

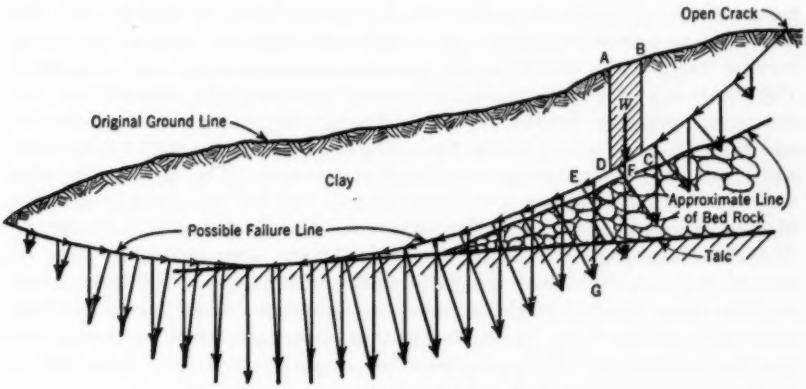

FIG. 2.—A SLIDE SHOWING THE SLIP-SURFACE

large-scale landslides, but increased expenditures and the increased likelihood of the loss of life in the event of failure require increased care and detail in the investigation and design.

The slide surface is sometimes believed to lie along the dipping strata of underlying rock, even though there is ample evidence of horizontal bedding. In areas of horizontal bedding, the bedrock that underlies earth masses often presents a "sloping" face to the overlying earth mass. However, this slope has developed by differential weathering or erosion of the various strata at the time the bedrock was exposed to air and water, and is a series of small vertical or sloping steps, as seen subsequently in Fig. 3. The over-all slope is dependent upon the nature of the bedrock, the length of time the face was exposed to weathering or erosion, and the geochemical and physical changes caused by percolating ground water.[5]

The fact that the force of gravity is the one cause common to all mass movements is too often subjugated to other factors, particularly to the effect of water. Constant use is made of drainage as a corrective action, and, although drainage should be considered, the fundamental basis for an analysis of a landslide correction is the principle that gravity is tending to move the material to the topographic bottom. From a practical viewpoint, the correction of some slides by drainage alone would result in an expenditure greater than the cost of the removal of the entire mass.[7]

Basic mechanics should be applied to all landslides. Several engineers have recognized the importance of mechanics in the study of earth movement. Mr. Terzaghi and Ralph B. Peck[8] (M. ASCE), D. P. Krynine[9] (M. ASCE), R. G. Hennes[10] (M. ASCE), Donald W. Taylor[11] (A. M. ASCE), T. W. Lambe[12] (J. M. ASCE), and others have discussed the use of theoretical formulas for estimating the forces at work. All of them wisely qualify the application of the theories. One section of a slide area along the Ohio River on the Neptune-Belleville Project in West Virginia is shown diagrammatically in Fig. 2.

The condition of stability of the area at the time of, and shortly after, the movement is such that the area is at or near the point of equilibrium. The fact that movement has taken place justifies the foregoing assumption. Also, because the sliding surface is curved, certain other factors are important. The location of the underlying strata was determined by core-borings, and the upper and lower breaks were identified by open, deep cracks at the top, and heaving (or rotation) at the toe. The slip-plane was determined by trial and error and by assuming no bedrock movement. The theories involved with the computations are somewhat complex but are described in detail by Messrs. Terzaghi and Peck, Mr. Krynine, Mr. Hennes, and others.[8,9,10] The shear characteristics of the clay overburden were estimated from the general soil conditions and the performance of adjacent cut slopes. Many boulders were found throughout the clay overburden. Hydrostatic pressures were not considered, nor were the location of seepage strata or the layer of talc in the bedrock. The conditions, in general, do not meet those for the application of elastic theories; however, basic principles of mechanics justify the approximations that were made.

In Fig. 2, the narrow segment ABCD is selected for study. Assuming that the slip-plane is straight for the part of the slide under consideration introduces an error well within the limits of accuracy. The earth exerts a downward force equal to its weight. This vertical force (FG) at any point of failure along the slip-plane has a component perpendicular to the plane of failure and another component parallel to the plane of failure. This resolution

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[7] "Earth Slip Hazards and Control in Highway Maintenance," by William S. Downs, *Engineering News-Record*, May 15, 1930, p. 794.

[8] "Soil Mechanics in Engineering Practice," by Karl Terzaghi and Ralph B. Peck, John Wiley & Sons Inc., New York, N. Y., 1948.

[9] "Soil Mechanics," by D. P. Krynine, McGraw-Hill Book Co., Inc., New York, N. Y., 1941.

[10] "Analysis and Control of Landslides," by Robert Graham Hennes, *Bulletin No. 91*, Univ. of Washington Eng. Experiment Station, Seattle, Wash., June, 1936.

[11] "Fundamentals of Soil Mechanics," by Donald W. Taylor, John Wiley & Sons, Inc., New York, N. Y., 1948.

[12] Discussion by T. W. Lambe of "Landslide Investigation and Correction," by Hyde Forbes, *Transactions*, ASCE, Vol. 112, 1947, p. 407.

of forces is indicated in Fig. 2. Those forces perpendicular to the plane are normal forces (EG), and those parallel to the plane are shear forces (EF). Further study of Fig. 2 shows that the shear forces are those that cause movement, and these forces are largest near the top of the slide. At the toe of the slope are the greatest part of the resisting normal forces as well as the shear forces that are acting to resist the slide due to the vertical or rotational effect.

The stability of the slope can be estimated by computing (1) the normal and shear forces for successive increments and (2) the total normal and shear forces. The width of the increment is governed by the accuracy desired. Considering a segment 1 ft wide, perpendicular to movement, the following equation represents the stability of the slope:

$$N = \frac{\sum F_n \tan\phi + c\,L}{\sum F_t} \qquad (1)$$

in which N is equal to the safety factor (1.0 at equilibrium); F_n represents the normal force, in tons; ϕ is the angle of internal friction; c denotes the cohesion, in tons per square foot; L is the length of the slip-plane, in feet; and F_t represents the shear force, in tons. The numerator represents the shearing resistance and the denominator equals the shearing forces. For clay soils with an angle of internal friction equal to 0°, the shearing resistance is equal to $c\,L$.

The shearing resistance can be estimated by assuming a safety factor of 1.0 as suggested by E. M. Buckingham,[13] A. M. ASCE. Although there have been instances in which slopes have remained stable at values of 0.8 for the safety factor, an estimate of relative stability can be obtained by assuming a value of 1.0.

From an analysis of Eq. 1 and a study of Fig. 2, it can be seen that earth removed from the top of the slide, or a load applied at the toe of the slope, will increase the value of N for the slope. Since the earth mass represents the major part of the force, any change in the distribution of the earth will have an important effect on the stability of the slope.

The principles of landslides, as represented in Fig. 2, are fundamental and essential to a clear understanding of nearly all corrective actions that can be taken. The following semirational analysis is based on evaluating the stability through estimates of the safety factor, in which the theories of hydrostatic pressures, seepage forces, undisturbed samples for shear determinations, and other refinements may be applied. The analysis is based on the weight of the mass acting vertically, with a component perpendicular to the slip-plane and another component parallel to the slip-plane. Also, the position and shape of the failure plane are approximated. The landslide must be at rest at or near the balance point between movement and stability, resisted by essentially the same shearing resistance that existed just prior to failure. Any method of correction can be evaluated immediately as being essentially helpful or primarily harmful on the basis of the suggested approach. An estimate of the degree of improvement is dependent on an estimate of the shear forces

[13] Discussion by E. M. Buckingham of "Landslide Investigation and Correction," by Hyde Forbes, *Transactions*, ASCE, Vol. 112, 1947, p. 435.

as well as the shearing resistance. This estimate will depend on shear test data or on an estimate of the shear resistance based on the conditions immediately prior to movement, or both.

The forces of gravity involved in debris-slides are as outlined in Fig. 3. For this type of movement, the ratio between the shear and normal forces will

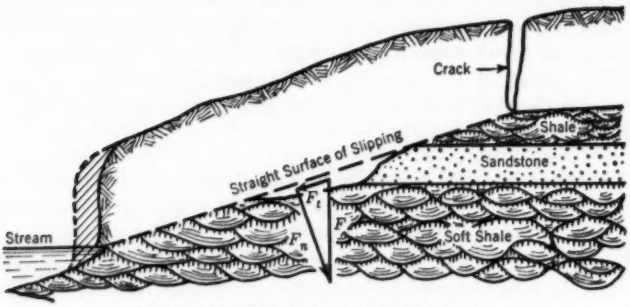

FIG. 3.—THE MECHANICS OF A DEBRIS-SLIDE

be equal to the tangent of the slope. The numerical value of the forces will be dependent on the amount of overburden, which will generally be largest at the toe of the slide. The movement cannot retain the classification of a debris-slide, as defined, unless the material that is sliding is cleared from the

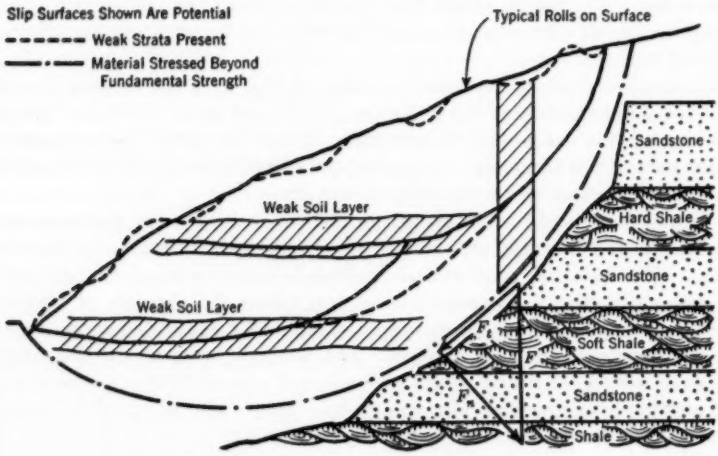

FIG. 4.—THE MECHANICS OF CREEP MOVEMENT

toe. If the material accumulates, the shape of the slip-surface will change from straight to curved, and a more stable situation will develop. Therefore, a debris-slide normally exists along a stream unless the toe is cleared by a highway maintenance crew. For debris-slides, a reduction of shear forces may be brought about by the removal of material from the sliding mass, but

the location of the removal is less important than in the case of landslides with a curved slip-plane. The degree of stability brought about by the removal of material is dependent on the slope of the slip-plane since the normal and shear forces are reduced by a constant proportion for a given condition.

For earth movements classified as either creep or flow, the analysis is more involved. The over-all stability should be estimated because these types commonly develop into landslides.[3] The mechanics resemble those of slide analyses, the differences lying in the irregular potential slip-surface of the creep movement and the lower shear characteristics of the flow type. Figs. 4 and 5 illustrate creep and flow movements. The ratio between shear and normal forces will vary, the assumed slip-plane being curved; and since this is a potential surface, it does not exist until an over-all failure occurs. For the control of the creep movement, corrective action should tend to reduce the load on any weak strata or on the entire earth mass. For flow movement, an effort

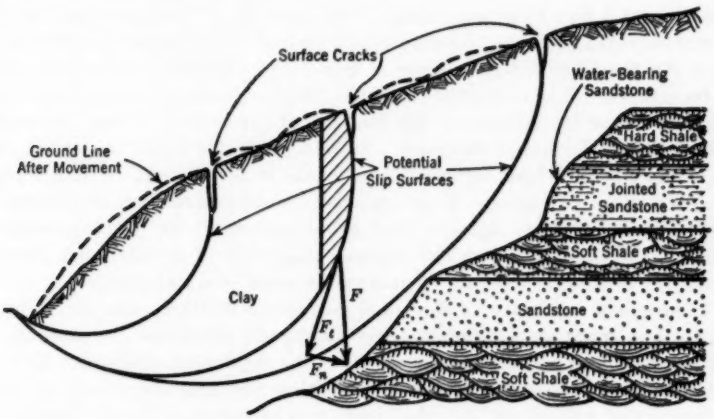

FIG. 5.—THE MECHANICS OF FLOW MOVEMENT

should be made to reduce shearing forces and to increase shearing resistance. Also, because the cohesive strength of the soil involved in this type of movement is low, the removal of water would aid in the control of flow. Retaining devices should not be designed to eliminate displacement entirely if the landslide is extensive since a large part of the weight of the soil mass should not be concentrated against a rigid resistance. Creep and flow failures are rare types, and because of the complicated nature of the movements, these failures should be referred to an authority in that field.

DISCUSSION OF METHODS OF CORRECTION

If the geomorphologists' land-forming hypothesis that landslides occur in a mass which is inevitably moving toward the topographic bottom of an area is accepted, it is important to realize that any method short of complete removal cannot be a permanent cure in terms of hundreds of years, and that the value and life expectancy of the structure are intimately associated with

the solution of the problem. Therefore, design life must be a factor in arriving at a solution to any landslide condition, and of all the factors involved in the design or investigation, none is more complex or difficult to estimate. The determination of the factors contributing to a landslide usually is possible. The absence of these factors will delay the movement for some finite period. In several cases with which the writer is familiar, the time variable for the occurrence or nonoccurrence of a given landslide, as influenced by one factor, could well have ranged from a few seconds to nearly fifty years. The only estimate for this phase of the mass-movement problem is the degree of stability in such terms as "obviously weak," "questionable," or "obviously safe." If, for instance, the slope appears to be "very safe," the area should be considered stable for an extended period of time. Continuing observations are desirable for several years.

Another consideration related to permanency and design life is the maintenance of landslides. A. V. Bowhay[14] referred to this consideration in a discussion of a San Francisco, Calif., landslide which was contained by oiling the surface periodically to prevent the entrance of surface water into the ground. When the thought of maintenance is introduced, the full implications should not be ignored. For example, although piling or blasting may result in bent, broken piles, or in settlement, the life cost of the method should be weighed against the performance required. It is conceivable that, in certain cases, two or three piles or blasting operations would be less expensive than a permanent correction. Of course, there are other considerations besides life cost and performances, such as failures that could endanger life and property. In addition, solutions based on the future availability of maintenance funds are unpopular because of the rapidly increasing costs of maintenance.

A complete summary of landslide corrective methods was listed by Mr. Ladd. For highway problems, some additional solutions are possible, and Table 1 lists and explains those methods for correcting landslides that were mentioned by Messrs. Ladd and Price, other methods suggested by various engineers and geologists, and the writer's experiences in West Virginia. No method, essentially different from those included, is knowingly omitted. Methods can be classified as permanent or expedient. Assuming good design and investigation, permanent solutions are considered satisfactory for at least a period of from twenty years to fifty years. Expedient methods are likely to serve for from one year to ten years. If good design practices are followed, all the corrective measures are considered permanent except the removal of material from the toe, "floating" piles, and blasting. Several of the corrective measures are recommended solely for use with other corrective measures and are rarely solutions in themselves.

The theory that landslides result from unbalanced forces leads to solutions based on changing the balance between contributing and resisting forces at work in or on the earth mass. All landslide control methods rely upon the restoration of balance for their success. A general distinction does exist as to whether the method attempts to rebalance by draining, retaining, direct

[14] Discussion by A. V. Bowhay of "Landslide Investigation and Correction," by Hyde Forbes, *Transactions*, ASCE, Vol. 112, 1947, p. 428.

TABLE 1.—FACTORS IN THE DESIGN OF CORRECTIVE MEASURES

Corrective measure	Best application	Principles involved	Remarks
1. Relocation	All types.	Structure moved to location where mass movement is not present. Permanent solution.	Due to degree of permanency, a very desirable solution. Very often this is the most economical solution. Its use will depend on obtaining a satisfactory line and grade.
2. Excavate, drain, and backfill	Shallow soil or deep soil in combination with light weight backfill.	The sliding mass is removed and the area stabilized by the removal of water and by improving foundation conditions. Permanent solution.	All slide material should be excavated to solid rock, drains placed to intercept seepage, and the area backfilled. Unless highly organic, the same soil can be used for backfill. Good construction methods must be used. Where bedrock is not encountered, stability estimates based on shear values of reworked soil should be made, and a 2-ft-deep granular course should be placed at the bottom.
3. Drainage: Surface Subsurface Jacked-in-place pipe Tunnels	Subsurface is good method for shallow soil. Tunnel and jacking good for deep soil when water source is deep.	Removal of water results in: (1) A lower density of the soil; (2) a higher soil cohesion; (3) an elimination of lubrication of slip plane; (4) a removal of excess hydrostatic pressure; (5) a removal of seepage forces. Permanent solutions.	Surface drainage should be assured for all types of corrective measures. Generally, drainage should be designed to intercept water before it enters the slide. In an impervious soil, the water source must be reached to be effective in controlling movement. Subsurface drainage may not be feasible due to the undermining of slide material above the excavation.
4. Removal of material: Entirely	Shallow soil.	Entire slide mass is removed. Permanent solution.	For shallow soil profiles, consideration should be given to a solution involving the entire removal of the slide. For deep soil profiles, the removal of material at the top of the slide will increase stability. For all removal corrections, undermining of areas should be considered. The removal of the material at the toe of a slide is rarely desirable, although at times necessary, in order to open a road for traffic. If the only corrective action applied is the removal from the toe, the slide will continue. Partial removal of material from the top has less influence on a debris slide.
Partial at toe	Clear road for traffic.	Condition relieved temporarily. Expedient solution.	
Partial at top	Deep soil.	A large part of the main source of shearing force is removed. Permanent solution.	
5. Buttress at toe	Good foundation at toe in shallow or deep soil. Buttress should extend below the slip plane.	Large mass blocks the mass movement and any further movement involves displacement of the buttress. Permanent solution.	An excellent method of correction when the situation at the toe permits. Action is that of a retaining device. Much less expensive than cribbing or a retaining wall. The buttress should be founded below the slip surface, for, unless the sliding material has an angle of internal friction greater than 15°, the added normal force of a buttress has little influence on the safety factor.

TABLE 1.—(*Continued*)

Corrective measure	Best application	Principles involved	Remarks
6. Bridging	Steep hillside locations with a narrow failure parallel to road in deep soil.	The troublesome area is bridged and future movement passes under the structure. Permanent solution.	Very satisfactory solution. The foundations must be bed rock that is not subject to movement or erosion. Too costly for general application.
7. Cribbing—timber, concrete, or metal	Shallow soil with good foundations.	A retaining mass, with or without additional lateral restraint, placed in path of the mass movement. Further movement involves displacement of the retaining mass. Permanent solution.	Good method where applicable but relatively costly. Less stable foundation required than for retaining wall as shifting is permissible before cribbing fails. Resistance offered is the weight of the crib unless bedrock is excavated to give resistance to lateral thrust. Recommended for shallow soil profiles. Weight of the crib-wall can be compared with weight of material removed for an estimate of the relative degree of stability offered by the cribbing. In slide areas, the resistance required can be estimated by using the formula for the safety factor. Not recommended in creep and flow areas.
8. Retaining wall of stone or concrete	Shallow soil with good foundations.	A retaining mass with lateral restraint, placed in path of the mass movement. Further movement involves displacement of the retaining wall. Permanent solution.	The applications are similar to those of cribbing. The cost is a deterrent. Walls are advantageous in urban areas. A wall requires a foundation in bedrock or good soil below the slip surface. Standard practice is to include weep holes in designing the wall. The formula for the safety factor may be used to estimate resistance required to lateral thrust. Retaining walls in creep and flow movements may take full weight of soil.
9. Piling:			
Floating	Shallow soil to hold temporarily.	Piling offers a retaining influence. For soil masses the piling may tend to "pin" the moving and stable materials, and bring about a more lengthy slip-surface with a corresponding increase in shearing resistance. Floating piles are expedients. All others are permanent solutions.	Floating piles do not appreciably penetrate bedrock or the slip-surface. As an expedient, such methods have lasted for from 1 year to 10 years. With a slip-surface at bedrock, the fixed piling penetrating for a distance of from 3 ft to 5 ft into bedrock, offers resistance equal to the force required to bend the piling. If the soil is wet and fine-grained, movement in the area is likely to be due to extrusion between the piles. For piling in deep soil, where the base of the pile penetrates 5 ft past the slip-surface, the recommendation of Krynine is to estimate the forces on a slip-surface curving under the piling.[a] Stability can be estimated by the formula for the safety factor. For piling with provisions for preventing extrusion (such as I-beam and cribbing combinations) the principles of a retaining wall apply.
Fixed—no provision for preventing extrusion	Shallow soil with numerous large rocks.		
Fixed—provision for preventing extrusion	Shallow soil.		
10. Sealing joint planes and open seams	Deep source of water.	The same benefits are sought as for a drainage solution. Permanent solution.	It is essential to locate the source of water and to block its entrance by grouting. Difficult to achieve and to estimate quantities. The effect of blocking the water should be studied for the area above and around the slide. This method of correction is still experimental.

[a] "Landslides and Pile Action," by D. P. Krynine, *Engineering News-Record*, Vol. 107, 1931, p. 860.

TABLE 1.—(*Continued*)

Corrective measure	Best application	Principles involved	Remarks
11. Cementation of loose material	Permeable material only, unless "column" principle is to be used.	An attempt to improve the shear characteristics of the soil. For "columns," the weight of the structure is carried to firm foundations. Some lateral restraint is offered. Permanent solution.	Stability is achieved by cementing the slide material. In order to produce deep soil stabilization, a permeable material is essential. By drilling holes and pressure grouting, columns of uncertain diameter will tend to stabilize the area even in clay soil. This method is experimental.
12. Chemical treatment—floculation	Permeable material.	Same principles as 11, except chemicals are used. Permanent solution.	This is essentially the same as cementation, except chemicals are used. The value of "columns" for clay materials is of less importance than for cementation. This method is experimental.
13. Tie-rodding slopes	Shallow soil with large rock fragments.	The retaining device insufficient to withstand movement is anchored to bedrock. Permanent solution.	A retaining device, such as steel plates or piles with cribbing, is anchored by steel bars to solid rock and is generally a costly operation. This method has been described by T. H. Cutler[b] and others.[c] The resistance to movement can be checked by the formula for the safety factor.
14. Blasting	Shallow soil underlain by good rock.	An attempt is made to disrupt the sliding surface as well as to develop a drainage system. An expedient solution.	The soil should be shallow with a hard rock underneath. The blast should be heavy, particularly at the toe. Recommended spacing is 6-ft centers in a T form. Explosive experts should be consulted as to size of charge. If used under an impermeable clay-soil, the method will be ineffective unless the source of water is tapped. Continued settlement of the area is to be expected. According to Mr. Ladd, the slip-surface will not be permanently broken up nor will drainage be effective indefinitely.
15. Reshaping slide material	Face of slide has open fissures. Benches cause ponding of water.	See 3. Method generally used in combination with other actions.	Area improved by sealing surface so as to prevent the entrance of water. Also removed "ponds."
16. Slope treatment	Shallow soil in combination with other methods, or any erosion problem.	See 3. Method generally used in combination with other actions.	Area improved by sealing surface so as to prevent the entrance of water, and to minimize erosion. Use seeding or sodding, blanketing with cinders, guniting, or oiling of surface.
17. Lightweight fill	In cases where loading is critical.	Reduction of the weight causing movement. Rarely a solution in itself.	The heavier soil is replaced with a lighter, permeable material. Often valuable when it is desirable to hold a given grade.

[b] "Slipping Road Fill Held Up by Steel Suspenders," by T. H. Cutler, *Engineering News-Record*, Vol. 109, 1932, p. 684. [c] "Device Prevents Slides on Road and Railway Fills," *ibid.*, Vol. 104, 1930, p. 787.

rebalancing of the forces, or some combination of these three. This difference in principle is indicated in Table 1.

Analyzing a Landslide for Corrective Measures

There are four factors about which information is needed to analyze a landslide for corrective measures. One of the most important is involved with the geology and geologic structure of the area. In movements involving only the soil overburden, this information will consist primarily of a topographic description of the surface of the underlying bedrock. It is essential, also, to determine if there is a movement of the bedrock material. The type, nature, and extent of the bedrock are important if the corrective action requires a solid foundation.

Also important is the location of seepage strata which might contribute to the landslide. This location may not be essential to the solution of the problem, but the knowledge of the location of the underground water is certain to result in a better understanding of the mechanics of the earth movement.

The third type of information needed is a topographic survey of the ground surface in the landslide area. Normally, this will be for the purpose of estimating either the costs or the degree of stability. A hand-level survey will be sufficiently accurate unless subsequent movements of the slide are to be measured.

Finally, information is needed about the soil. The required detail will vary; however, data giving the unit weight, moisture content, gradation, and plasticity characteristics are almost always necessary. For this information the shear characteristics can often be estimated with sufficient accuracy. Until good approximations of shear data can be made, undisturbed soil samples may be required. The status of the corrective actions for landslides is not sufficiently well developed to permit too high a degree of refinement. When the problem is obviously complex or the investment involved is large, the engineer must recognize the need for a specialist. Otherwise, the refinements need not be more than those recognized by highway engineers.

In analyzing a landslide relative to solving a highway problem, the first step is a preliminary field study. This is followed by a detailed field study, an office investigation, and, finally, a construction and supplemental investigation. In some cases, primarily those involving relocation projects or very small-scale movements, the second and third steps may be practically eliminated.

Preliminary Field Investigation.—In the preliminary field investigation, the area should be carefully inspected and the landslide classified. The depth of the soil mass, the boundaries of the moving area, and the relation of the structure to the movement are then estimated. From these, the type of corrective measures that seems feasible is determined and the information needed for the design of the corrective measures is indicated.

The slide should be classified as either a slide, a debris slide, a creep, a flow, or a rock movement. The depth of the soil mass is a critical factor in arriving at an adequate design. Normally this depth is determined by subsurface exploration. However, as an aid in estimating the probable corrective

actions, the preliminary reconnaissance should state whether the soil mass is likely to be deeper than 15 ft. This depth is the approximate dividing line between the values of shallow and deep soil profiles discussed in Table 1. The best guides to approximate soil depth are excavations in the area and the steepness of the slope in the slide area. Generally, steeper slopes will have relatively shallow soil profiles. A familiarity with land forms will aid materially. However, experience is the best guide in estimating soil depths.

The outline of the displaced area is normally quite simple to identify. Active slides and debris-slides are accompanied by characteristic open cracks in the earth's surface as seen in Fig. 6. Creep may have (and flows will have) cracks near the top of the area. Normally, it is assumed that failure has not occurred in the area above the last open crack. Movement cracks are readily

FIG. 6.—DELINEATION OF A SLIDE AREA BY OPEN CRACKS

differentiated from shrinkage cracks since the former are perpendicular to the movement of the landslide. In some instances, smaller cracks may appear above the last pronounced crack due to a secondary failure caused by the primary movement. In such cases, the secondary failures should be included in the analysis. The toe of the slide is unmistakable even though the landslide occurred some time previously. It is characterized by either an unnatural, vertical hump that appears to have been lifted or rotated, as in Fig. 7, or a roll that has apparently been shoved laterally over a firm base. The toe is normally at the topographic bottom of the area, although exceptions to this are not uncommon. At times, the lateral extent of creep or flow is difficult to determine but it may be assumed that failure has not occurred beyond the limits of the cracks in the earth's surface.

The best corrective action for the landslide will vary considerably with the location of the structure relative to the movement. Any location other than the top or the toe of the landslide is likely to have a stability problem both above and below the structure. The relative position of the structure can be determined after the boundaries have been established.

A fundamental assumption to the analysis is that there is more than one solution to an earth-movement problem, and certain types of corrective actions do not require complete investigations. Also, it is assumed that the mechanics, rather than the cause, of the landslide are the more important issue. Therefore, only the information needed for corrective action need be obtained. Arriving at an accurate preliminary estimate is the step most subject to the experience of the investigator. This estimate will vary not only

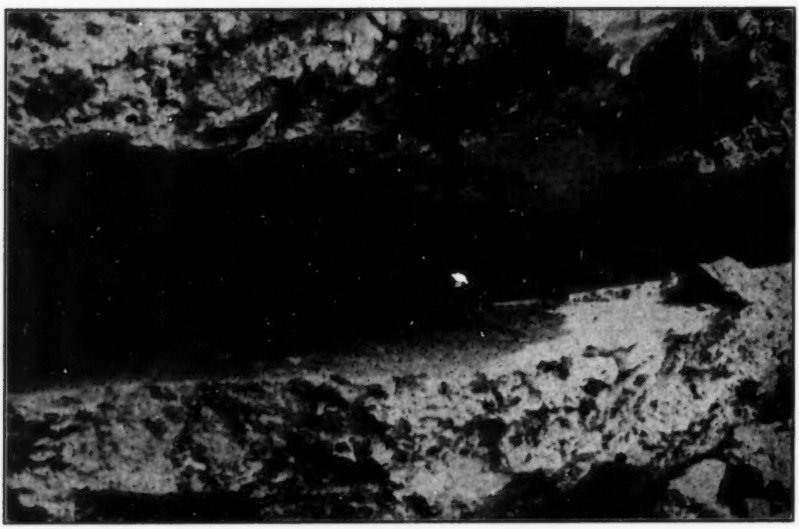

FIG. 7.—SLICK SURFACE OF THE SLIDE-PLANE

with the investigator but with the area involved, and the type and value of the structure to be safeguarded. However, failure to estimate accurately the corrective action should result only in a higher investigational cost.

In considering which of the corrective methods will be feasible, many will be eliminated easily, because of obvious nonapplicability. For the remaining corrective measures, rough estimates will indicate an extremely expensive action, relative to the estimates for other measures. The expensive corrective actions should then be dropped from further consideration until the less expensive methods prove unfeasible.

For each method of correction, certain information is considered essential to produce design data. Table 2 is a summary of the data needed for the design computations for each of the methods. Details relative to the costs of the

TABLE 2.—INVESTIGATION NEEDED FOR VARIOUS CORRECTIVE MEASURES

Corrective measure	Topographic survey ground surface	Bedrock profile	Source of water	Undisturbed soil sample	General soil condition
1. Relocation	For new location only.	Sometimes needed to check stability of new area.	No	No	No
2. Excavation, drain, and backfill	Area and depth for cost and stability estimates.	Depth for cost and stability estimates.	For cost, drainage, and stability estimates.	Not essential.	Moisture content for locating water and soil characteristics for estimating shear data.
3. Drainage: Surface, Subsurface, Jacked-in-place pipe, Tunnels	For depths and lengths in cost estimates for all but surface drainage.	For depths, lengths, and cost estimates for all but surface drainage.	For locating position of drainage installation.	Essential for permeability only if drainage is to be installed to drain soil, rather than to intercept seepage strata.	Moisture content for locating water source.
4. Removal of material:					
Entirely	For cost estimate only.	For cost estimate only.	No	No	No
Partial at toe	For cost estimate (partial survey).	No	No	No	No
Partial at top	For cost and stability estimates.	Surface only, for cost and stability estimates.	Not essential.	To compute stability of slope.	Density and moisture variations for stability estimates.
5. Buttress at toe	For stability estimate.	Surface only, for stability estimate.	Not essential.	For stability estimate.	Density and moisture variations for stability estimates.
6. Bridging	At abutments only, for cost estimate.	At abutments only, to determine foundations.	Not essential.	At abutments if spread footers are used.	Not essential.
7. Cribbing—timber, concrete, metal	For computing forces against wall, and height determinations.	For depth to foundation, type of foundation, and stability estimate.	Not essential.	To compute forces against wall.	Density and moisture variations for stability estimate.

TABLE 2.—(*Continued*)

Corrective measure	Topographic survey ground surface	Bedrock profile	Source of water	Undisturbed soil sample	General soil condition
8. Retaining wall (stone or concrete)	For computing forces against wall and height determinations.	For depth to foundation, type of foundation, and stability estimate.	Not essential.	To compute forces against wall.	Density and moisture variations for stability estimate.
9. Piling:					
Floating	Partly for soil depths in cost estimate.	Partly for soil depths in cost estimate.	No	No	For moisture and gradation for determining flow possibilities.
Fixed, no provision for preventing intrusion	For soil depth in cost estimate.	For soil depth in cost estimate and type of foundation.	Not essential.	Not essential.	For moisture and gradation for determining flow possibilities.
Fixed, provision for preventing intrusion	For soil depth in cost estimate.	For soil depth in cost estimate and type of foundation.	Not essential.	To compute forces.	For density and moisture in determining stability.
10. Sealing joint planes and open seams	For depths in cost estimate.	For determining strata to be blocked.	For determining strata to be blocked.	No	No
11. Cementation of loose material	For depth and area in cost estimate.	Surface only for cost estimate.	Not essential.	For determining permeability to cementing material.	Density, moisture, gradation for determining feasibility of method.
12. Chemical treatments—flocculation	For depth and area in cost estimate.	Surface only for cost estimate.	Not essential.	For determining permeability to chemicals.	Density, moisture, texture for determining feasibility of method.
13. Tie-rodding slopes	Area and depth for stability and cost estimates.	For depth in cost and stability estimates. Also type of foundation.	Not essential.	For stability estimate.	For texture, moisture and density for stability estimate.
14. Blasting	For depths in cost estimates.	For depth in cost estimate and type of rock.	Not essential.	Not essential.	Density and moisture.
15. Reshaping slide material	For cost estimate.	No	Not essential.	No	No
16. Slope treatment	Area for cost estimate only.	No	Not essential.	Not essential.	For agricultural purposes or for texture.
17. Lightweight fill	Depth and area for cost and stability estimates.	Surface only for depth in stability estimate.	Not essential.	For load reduction in stability estimate.	Density for stability estimate.

corrective actions are vital information in the design, and Table 3 shows the estimates of costs based on average prices in West Virginia in 1950.

Detailed Field Investigation.—An excellent summary of subsurface exploration methods has been prepared by M. Juul Hvorslev,[15] M. ASCE. The importance of geology in subsurface work is to be emphasized. The proper interpretation of land forms, exposed bedrock, and the general geologic conditions of the area will greatly expedite the subsurface investigation. One of the most troublesome deficiencies in a rational correction of landslide problems is the

TABLE 3.—1950 UNIT COSTS FOR USE IN ESTIMATING EXPENDITURES FOR CORRECTIVE MEASURES

Corrective measure	Item	Cost, in dollars	Unit
1. Relocation	Excavation	0.75	Cubic yard
	Pavement	3.00	Square yard[a]
	Right of way	Variable	
2. Excavate, drain, and backfill	Excavation	3.50	Cubic yard[b]
	Drainage pipe	1.00	Foot[c]
3. Drainage[d]	Drainage pipe	1.00	Foot[c]
	Excavation	3.00	Cubic yard
	Porous backfill	2.50	Cubic yard[e]
	Jacked-in-place pipe	2.00	Foot[f]
4. Removal of material[d]	Excavation	0.75	Cubic yard
	Right of way	Variable	
5. Buttress at toe	Excavation	1.00	Cubic yard
	Backfill	3.00	Cubic yard
	Drainage pipe	1.00	Foot
	Right of way	Variable	
6. Bridging	Roadway surface	15.00	Square foot
7. Cribbing[d]	Face of cribbing	4.00	Square foot[g]
8. Retaining wall[d]	Face of wall	7.00	Square foot[g]
9. Piling[d]	Length of pile	5.00	Foot[h]
10. Sealing joint planes and open seams	Equipment rental	75.00	Day
	Drilling	3.00	Foot
	Cement	4.00	Barrel[d]
11. Cementation of loose material	Equipment rental	75.00	Day
	Drilling	3.00	Foot
	Cement	4.00	Barrel[e,i]
12. Chemical treatments—flocculation	Equipment rental	75.00	Day
	Drilling	3.00	Foot[j]
	Admixture	Variable	
13. Tie-rodding slopes	Length of pile	5.00	Foot[h]
	Drilling	3.00	Foot
	Steel	0.20	Pound[e]
	Concrete	45.00	Cubic yard[e]
14. Blasting	Drilling	3.00	Foot
	Black powder	.....	

[a] For flexible type pavement. [b] Earth moved twice. [c] Perforated pipe 6 in. in diameter. [d] Subheadings same as in Tables 1 and 2. [e] In place. [f] Pipe 6 in. in diameter, in place. [g] In place, 8 ft high, gravity-type concrete. [h] Steel, in place. [i] Quantities difficult to estimate.

lack of an efficient, practicable, and direct method of obtaining subsurface information. The uses of the hand auger, the test pits, the power auger, the well-drill, the churn-drill, the core-drill, and the geophysical surveys are the most common methods for obtaining this information. There is, also, the method suggested by Mr. Forbes, which is that of obtaining information during the construction phase of the corrective measure.

The most generally used method is core-drilling in conjunction with steel casing driven through the overburden material. Unfortunately, the cost of

[15] "Sub-surface Exploration and Sampling of Soils for Civil Engineering Purposes," by M. Juul Hvorslev, Report of a Research Project of the ASCE, The Eng. Foundation, Harvard Univ., Cambridge, Mass., 1950.

core-drilling is relatively high, ranging in West Virginia (in 1950) from $2.75 per ft to $5.00 per ft. The area must be very thoroughly and systematically drilled if a complete picture of the subsurface condition is to be obtained. The "checker-board" layout, similar to that used for topographic surveying, is sometimes used.

Of the two hand-methods, the auger is by far the cheaper and more generally applicable. A good two-man crew should average from 50 ft to 60 ft of investigation per day, for hole depths of from 10 ft to 14 ft. One advantage of this method is the reliable information that can be obtained about the variation of the soil and the moisture conditions. With additional equipment, relatively undisturbed samples can be removed. There are several limitations, however, the first being that rarely will a crew be able to bore deeper than 15 ft and the second being that the auger is stopped by rock boulders and most bedrock.

Test pits produce excellent information and often prove to be desirable, if subsurface drainage is a probable method of correction. However, the pits are uneconomical if numerous holes are needed in the design. The depth that can be reached is limited to from 10 ft to 15 ft unless problems of shoring and earth removal are solved.

If information at depths in excess of 15 ft is needed, power equipment is almost a necessity. Power augers are economical, the operating costs ranging from one third to one half that of core-drilling. Detailed soil information is sometimes difficult to obtain with power augers because many of the boring-rigs for deep work do not allow frequent withdrawals, nor do they cut through hard boulders or bedrock material. Even light rigs can drill to depths of from 60 ft to 75 ft.

Well-drills and churn-drills will penetrate bedrock and disclose the existence of seepage layers. The cost is approximately the same as for power augers. Since cores are not obtained, the type and character of the bedrock cannot be determined conclusively.

The subsurface methods holding the most promise are geophysical surveys, of either the electrical resistivity type or the seismic type. Since these methods are conducted from the surface, limited core-drilling for correlation purposes is usually desirable. Unfortunately, there have been very few efforts to apply these techniques to landslides. The initial efforts to use electrical resistivity surveys in West Virginia showed a surprisingly small difference of resistance between the soil and the bedrock shale and sandstone. The recent geophysical successes in highway engineering seem to justify the belief that eventually electrical resistivity and seismic methods will facilitate subsurface investigations of landslides. The cost of these studies may be as low as one tenth the cost of core-drilling.

In searching for underlying sources of water, it is well to realize that water generally follows a pattern in making its way through bedrock. The type of layer the water is traveling through may be observed in open cuts. Generally, water will travel through jointed sandstone or limestone and avoid the impervious shales. There are exceptions, of course. Water also is found seeping through the contact between soil and bedrock, or at the contact

between embankment and foundation soil. In coal areas, water is likely to be located just above the coal seam.

The presence of tilted trees, posts, poles, or structures is valuable evidence in locating a sliding surface. This not only verifies the fact that movement of the area has taken place, but also indicates the possibility that the depth of movement does not exceed the depth reached by the roots or the foundations. It is not uncommon to see landslides upon which trees, poles, and houses have moved horizontally and downward with little or no disturbance of vertical alinement. Obviously, such cases involve a slide plane that is deeper than the depth penetrated by the tilted object. The location of the slip-plane may be obtained from the drill records.

Office Investigation.—The office investigation will consist of plotting data, computing the forces at work, designing the corrective action, estimating the cost for the corrective action, and preparing a final report.

The plotting of data concerning slides will be routine and should show cross sections of the existing ground surface, the underlying bedrock, the location of drill holes, the data from the drill holes, the seepage strata, the pavements or structures, and other information considered pertinent to the slide. The number of cross sections will vary, depending on the detail desired; for example, in a study involving a narrow area (100 ft) the distance between sections may be as short as 25 ft. Cross sections should be available on the solid areas immediately adjacent to each end of the slide. The sections should be continued above and below the slide so that a complete analysis of the effects of a corrective action can be anticipated. In some cases, sections perpendicular to the movement will be desirable.

A plan view is normally included showing the general limits of the slide area, the location of drill holes and corrective action, and other pertinent information. The best possible estimate of the location of the plane of failure should be made. The notes of the field work should be studied closely for evidences determined from visual examination and from the drill work.

The shearing resistance or the shearing forces should be estimated following the principles previously outlined, and more completely covered by Messrs Terzaghi and Peck,[8] Mr. Krynine,[9] Mr. Hennes,[10] Mr. Buckingham,[13] and others.

Upon obtaining an estimate of the stability of the area before the failure, the safety factor should be computed to determine the advantage produced by the corrective action. The final corrective action should result in a more stable area than existed prior to the movement. The extent of improvement is dependent upon the economy of producing such stability. All else being equal, the method with the greatest safety factor is the most desirable.

Unless measurements and analyses are made to determine the influence of hydrostatic pressures and seepage forces, rarely will it be feasible to estimate, in terms of the safety factor, the benefit achieved by a drainage solution. Failure to take account of the many variables may produce a misleading safety factor; however, this refinement may be advisable under certain conditions. If the factor is neglected in both the "before failure" and "after correction" computations, the estimate will be on the safe side, except in

cases where the corrective measure increases the excess hydrostatic pressure or seepage forces, or where the pressures existed during failure but not after movement ceased.

The investigation of debris-slides will be essentially the same as that for slides, differing in the fact that the surface of failure will be straight, and the reshaping or terracing of the area will not be more effective than a uniform reduction of the slope. The stability estimate will be a relatively simple application of the more complicated slide approach because the entire weight may be used instead of dividing the area into sections, as in Fig. 3. Corrective actions for this type are influenced greatly by the slope of the slip-plane, and the displacement is more likely to have been caused by excess hydrostatic pressures or seepage forces.

For creep investigations, cross sections and a plan view are desirable. There is presumed, by definition, to be no plane of failure. In the investigation, emphasis should be placed on the accurate location of the weaker strata as well as seepage phenomena. Data relative to the surface of the bedrock are also of value. If one accepts the theory of Mr. Terzaghi—that successive failures of weak layers or the existence of stresses greater than the fundamental strength cause creep—the design should tend to alleviate the overstressed conditions. The over-all stability should be estimated because the movement often develops into a slide. The weak layers undoubtedly will influence the slip-plane, as in Fig. 4. The conditions of hydrostatic pressures and seepage forces are more important in this type of failure than in the previously mentioned types, and a more specialized approach is necessary.

By definition, flow has no plane of failure, but has a more rapid movement than creep, and generally results from excessive moisture. Such failures may be caused by failure of the weaker strata. If this is the case, then the movement is classified as creep. Since excessive moisture is the principal contributor, a drainage solution should be found. The over-all slope stability is important because these movements tend to develop into slides, as seen in Fig. 5.

Construction and Supplemental Investigations.—If the preliminary and abbreviated field investigations indicate that one type of corrective action is the most feasible solution, it is often desirable to combine with the construction a more complete investigation. This is particularly true for deep drainage solutions. This technique has been used to some extent by Mr. Forbes. For any corrective measure, sight should not be lost of the fact that the existing methods of subsurface exploration are not infallible. The construction should be watched and the corrective measure, bedrock layers, and seepage strata should be restudied. The drainage of all water-bearing strata or pockets should be worked into any corrective measure as an additional safety factor. If the construction exposes conditions not anticipated in the design, the corrective action must be re-evaluated.

For an indefinite period after completing the corrective action, observations should be continued. Any evidences of movement should be studied, and, if necessary, further corrective actions should be undertaken. Immediate action in such cases is very important, in order to make full use of the original corrective action.

Conclusion

The following facts and ideas have been presented in this study:

1. For landslides with slip-surfaces at or near the contact between soil and bedrock, a shear failure occurs in the soil.

2. All earth-movement problems can be corrected, but it is not always economically feasible to do so.

3. There are numerous instances in which the determination of "the" cause has only academic interest since the elimination of one or more "contributing factors" will bring about a higher degree of stability.

4. The presence of the force of gravity in every mass-movement problem should be a fundamental consideration. The earth mass represents not only the source of the trouble but also an economical source of resistance. The best method of appling these facts is through estimates based on the theories of soil mechanics. These theories involve the shear characteristics of the soil.

5. An inexpensive method of subsurface invesrigation is needed. Very few earth-movement problems can be satisfactorily considered without knowledge of subsurface conditions.

6. The method suggested herein for estimating the degree of stability for a corrective measure for a given situation is a step toward a rational analysis of earth movements. However, considerable development and extended observations are required before the method will progress to a fully rational procedure.

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